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Technology Forecasting For Space Communication

Executive Summary

NASA Contract ■ NAS 5-22057

JUNE 1973

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Prepared For
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GREENBELT, MARYLAND

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SCG 40000R

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TECHNOLOGY FORECASTING FOR SPACE COMMUNICATIONS

INTRODUCTION

The technology forecasting performed under this contract, NAS 5-22057, was designed to:

1) Provide the Goddard Space Flight Center (GSFC) spaceflight tracking and data network with current and projected state of the art performance for parameters, components, and systems used in space communications and integrally related systems; and

2) Provide cost effectiveness evaluations and tradeoffs for different component and system configurations based on a broad range of mission profiles.

To achieve these purposes six individual tasks have been assigned by the GSFC. These have been reported in five* individually bound task reports and, republished, constitute the main body of the final report volume.

Table 1 relates the several nomenclatures associated with the tasks and the task objectives. Basically the first five tasks assigned tend to support the final task, "Spacecraft Communication Terminal Evaluation," in which spacecraft communication terminals were compared on the basis of weight. Systems compared included both optical and radio systems.

The background for this technology forecasting is found in Contract NAS 5-9637. Here a rather comprehensive documentation was made of space communication hardware. Further, the concept of system design to minimize spacecraft weight was originated under that contract. The present effort has examined current hardware status and projected cost and performance of future systems.

The material which follows is an Executive Summary of the results of the several tasks. This in turn is followed by a listing of specific recommendations resulting from the task studies. The last part of this final report is the set of the five task reports. These are included only in the complete final report and are not included in the separately bound Executive Summary.

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*Two tasks were combined in one report (see Table 1).

TABLE 1. TECHNOLOGY FORECASTING FOR SPACE COMMUNICATIONS

Task Report Title	Task Objective	Comments	Contract Task Assignment No.
Task One Report: Optical System Study	To perform a parametric study of the elements required for the optical train of a laser communication system. The analysis will include all optical elements. The study will relate optical parameters such as output beam diameter, field of view, f-stop, detector area, and laser beam diameters to the structural dimensions of the optical train.		831-001
Task Five Report: Laser Communications for Data Acquisition Networks	To review laser communications technology and estimate future laser communications performance at specific time periods for inclusion in spaceflight data acquisition ground networks.	Includes task assignment 831-002.	831-005
(Quick reponse task)	Update Figure B, page 35, Vol. II, Final Report for "Parametric Analysis of Microwave and Laser Systems for Communication and Tracking," October 1969, prepared by Hughes Aircraft Co., Culver City, California, for GSFC, Tech. Dir. Dr. F. Kalil, Contract NAS 5-9637.	Included in "Task Five Report: Laser Communications for Data Acquisition."	831-002
Task Four: Telemetry, Command, and Data Handling	To provide a technology forecast of telemetry, command, and data handling subsystems, both spaceborne and ground, with cost effectiveness evaluations and recommendations for future research and applications.	Task could more appropriately have been entitled "Task 7: Telemetry, Command, and Data Handling."	860.3-007
Task Three Report: STDN Antenna and Preamplifier Cost Tradeoff Study	To determine a cost effective preamplifier antenna combination for the 1980s or next generation STDN ground stations. The study will consider S, X, and K bands, two antenna sizes, four preamplifier types, and rain for a typical station location.		831-003
	To perform a cost effectiveness tradeoff study of microwave solid state and vacuum tube power sources. These would include transistor amplifiers, tunnel diode amplifiers, IMPATT and Gunn Amplifiers, oscillators, and traveling wave tube amplifiers, and would provide the present and projected (1980 era) state of the art weight and cost tradeoffs and relative weight and cost benefits and recommendations.	The effort of Task 831-004, Transmitting Sources, was redirected and applied to expanding Task 860.3-006 to include S band, X band, and K band transmitting weight comparisons in addition to the laser analyses as defined in Task 006.	831-004
Task Six Report: Spacecraft Communication Terminal Evaluation	To provide a tradeoff study of the two most promising types of future laser communication systems, i.e., a 10.6 micron homodyne link and a 0.53 and 1.06 micron direct detection link. It will provide evaluations and recommendations for future research and applications.	Includes S band, X band, and K band comparisons as redirected from Task 831-004.	860.3-006

SUMMARY

The scope of "Technology Forecasting for Space Communications" is very wide, covering virtually every technology that can directly or indirectly affect space communications. The assigned effort, however, was directed toward a series of studies which individually examined important aspects of space communications and which collectively was interrelated. The contributions of the individual tasks and their interrelationship are indicated by Figure 1.

The total effort of the tasks was fairly evenly divided between laser oriented and radio frequency tasks. The investigations show that laser communications have a current state of the art which would allow operational systems to be implemented in the 1975 to 1980 time frame. Further, these systems, when operated over ranges in the order of synchronous ranges (42, 000 km) and transmitting data rates of 10^8 to 10^9 bps, will have a smaller total weight impact on a spacecraft than do radio systems.

The tasks dealing with RF communication indicate that the transistor amplifiers are rapidly outstripping tunnel diode amplifiers as low noise preamplifiers. Additionally, the uncooled and cooled parametric amplifiers have significantly increased ground station performance, with the latter becoming quite competitive with masers in a system configuration.

Projected improvements in ground station performance, available in part through improved feed configurations, are found in the higher frequencies, in lower transmission line losses, and in improved antenna efficiencies.

TASK SUMMARIES

Optical Systems Study

The purpose of this study was to define the weight impact of the components which might typically be found in an optical space communication system.

Figure 2 illustrates schematically the optical features of a typical spaceborne laser communication system. The spacecraft transmitter aperture is always diffraction-limited and is always pointed at the receiver with an angular pointing error which is small in comparison to the diffraction beam spread. The pointing is generally accomplished by means of separate coarse and fine pointing mechanisms. The coarse mechanism points the entire antenna while the fine pointing system moves a small optical component(s) to adjust the transmitter and receiver line of sight.

The boresight error between the transmitter and receiver optics in the transceiver must be small compared to the diffraction angle of the transmitter antenna. This requirement has led to the practice of having the transmitter and receiver share the same antenna. Advantages gained from this configuration include smaller transceiver size and weight and simplified

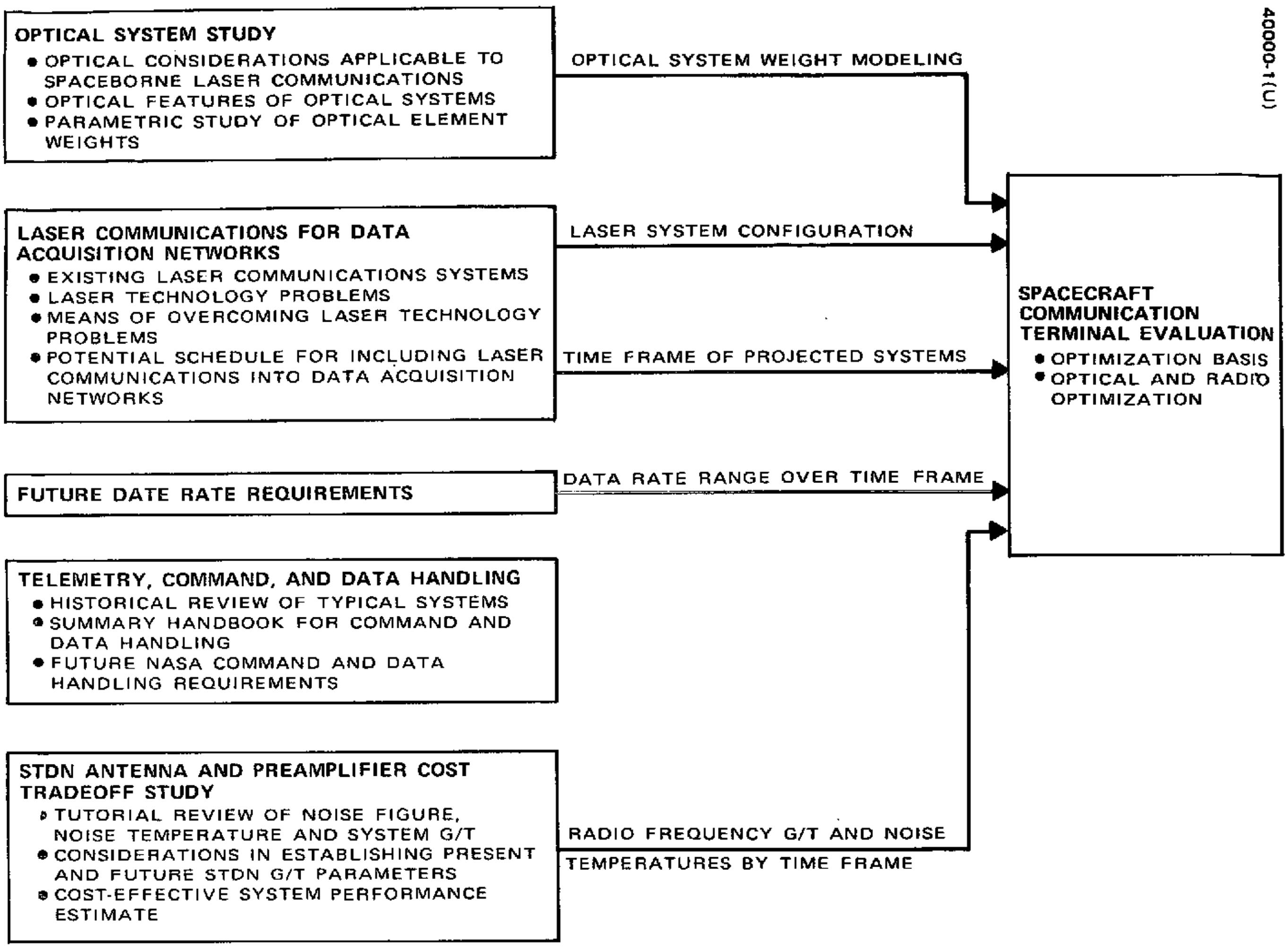

FIGURE 1. TECHNOLOGY FORECASTING TASKS AND THEIR INTERRELATIONSHIPS

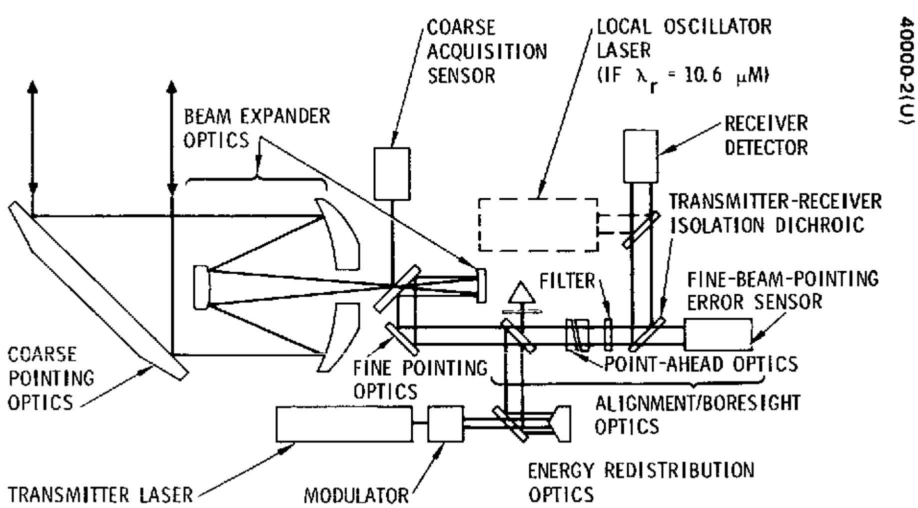

FIGURE 2. REPRESENTATIVE SPACEBORNE COMMUNICATION SYSTEM OPTICAL SCHEMATIC

boresighting procedures. However, with such a configuration, it is necessary to operate the transmitter and receiver on different laser frequencies to maintain proper signal separation.

For trajectories where the relative station velocities orthogonal to the line of sight cause a significant point-ahead angle,* a deliberate offset must be added to the boresight adjustment between receiver and transmitter. An alternate solution is to maintain a transmitted beam which is significantly wider than the point-ahead angle.

Table 2 lists the weights of the optical features. For simplicity, the optical elements following the beam expander were assumed to remain constant to accommodate an approximate 0.6 inch diameter output aperture. The weights assumed for the beam expander and coarse pointing assemblies as a function of aperture diameter are shown in Figure 3a. Then the weight budget assumptions in Figure 3a and Table 2 were combined and plotted in Figure 3b for the total estimated weight versus aperture diameter for a space communications optical sensor less the receiver and transmitter.

It must be emphasized that the data in Figure 3b represent an estimate of sensor weight based upon existing and currently proposed infrared space optical systems. Weight variations will exist as a function of such parameters as wavelength, optical element f number, feature inclusion, thermal control requirements, baffling requirements, and, perhaps most important of all, development effort for weight reduction.

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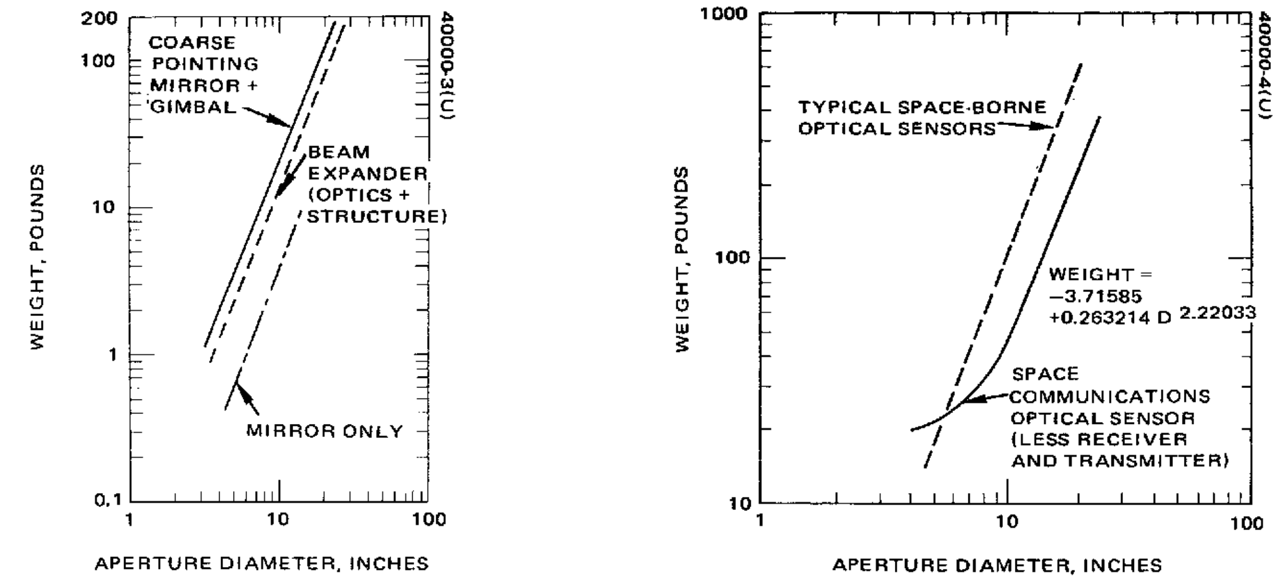
*The point-ahead angle is equal to $2\,\frac{v}{c}$ where v is the relative station velocity orthogonal to the line of sight between stations and c is the velocity of light.

TABLE 2. OPTO-MECHANICAL WEIGHT BUDGET*

1)	Beam expander (Optics + structure)	See Figure 3a
2)	Coarse pointing (Mirror + gimbal)	See Figure 3a
3)	Fine pointing	2.0 lb
4)	Coarse acquisition sensor	3.0 lb
5)	Fine-beam-pointing error sensor (Including isolation filter)	4.1 lb
6)	Point-ahead optics	2.0 lb
7)	Multiplex beamsplitter	0.05 lb
8)	Energy redistribution device	0.10 lb
9)	Alignment and boresight optics (Corner cube and shutter only)	0.25 lb
		11.50 lb + beam expander and coarse pointing

*Moderate thermal control and baffling assumed does not include 1) receiver detector or local oscillator, 2) transmitter laser and modulator, 3) electronics.



a) FOR COARSE POINTING AND BEAM EXPANDER

b) FOR SPACE COMMUNICATIONS OPTICAL SENSOR

FIGURE 3. ESTIMATED WEIGHT VERSUS APERTURE DIAMETER

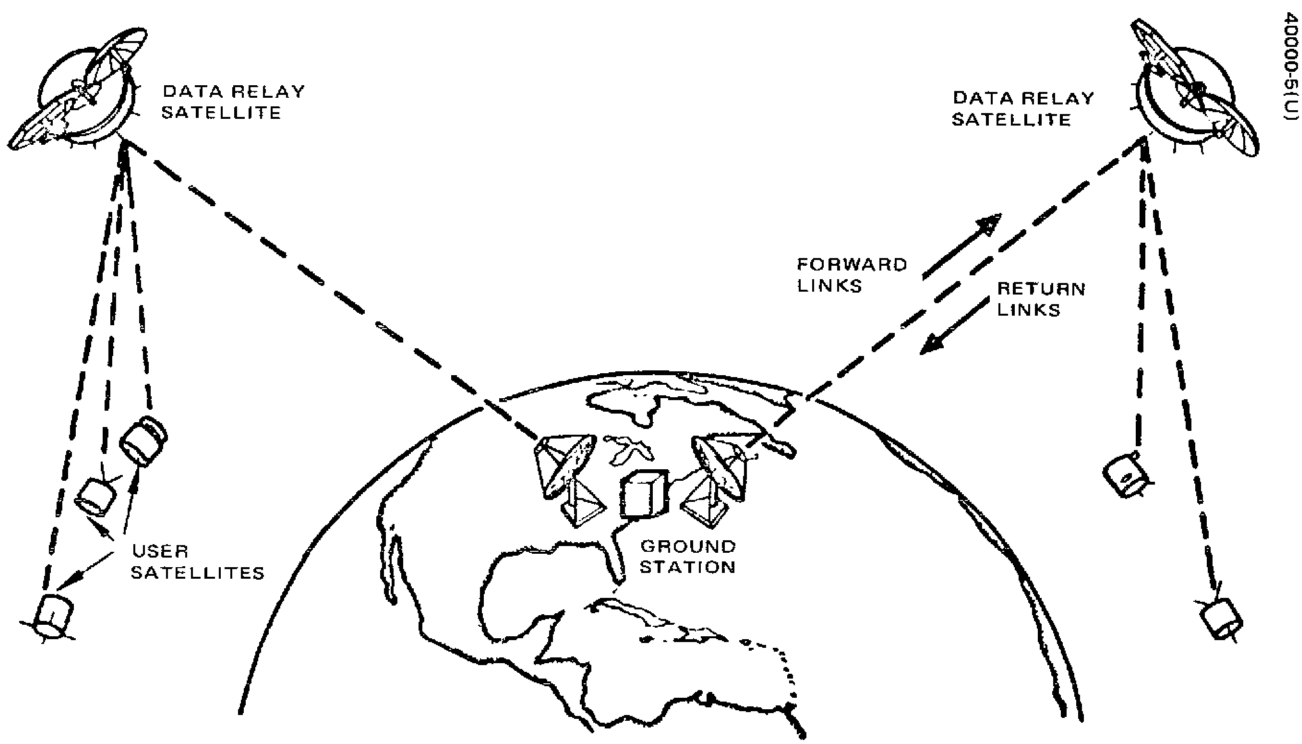


FIGURE 4. DATA RELAY SATELLITE CONCEPT

Laser Communications for Data Acquisition Networks

A radical new step in obtaining data from scientific satellites is the data relay satellite concept, shown in Figure 4. In this concept, a data relay satellite is utilized to relay data and commands between low earth orbiting user satellites and a central ground station. The data relay satellite must operate at a variety of frequencies to accommodate the current scientific user satellites. A data relay satellite system can, however, replace a large number of ground stations and is, therefore, economically attractive. Two system definition studies have now been completed which establish design concepts of a data relay satellite system operating in the RF spectrum.

In order to determine the suitability of a laser communication system for space, a number of system related factors should be considered. The most significant of these are listed in Table 3 with a brief explanation. Collectively these factors help to distinguish the strong candidate systems from weak systems. In the final analysis, a summary design of the best candidate systems to meet the mission requirements must be completed before a candidate system can be selected as being best. This is done in Task 6, "Spacecraft Communication Terminal Evaluation," for a CO_2 laser system and a Nd:YAG laser system.

Eleven prospective laser communication systems were evaluated and compared using the factors of Table 4. A figure of merit can be defined which is a product of several of these factors. The figure of merit, M, is: (laser efficiency) x (modulator figure-of-merit) x (bandwidth) x $(P_T/P_R)_{min}$ x (λ). Laser efficiency and modulator figure-of-merit are related to performance per unit power required, whereas the bandwidth and $(P_T/P_R)_{min}$ relate to the channel capacity. The wavelength factor takes into account the narrower beamwidths which can be achieved at the shorter wavelengths. The more difficult pointing task at the shorter wavelengths is not included in this comparison. The values for M, given in Table 4, are normalized to unity for the

TABLE 3. FACTORS USED IN EVALUATING LASERS FOR COMMUNICATION SYSTEMS

P_T/P_R min	Ratio of available optical transmitter power to minimum detectable optical signal power per hertz of bandwidth ($P_T\eta_o/hf$). This factor is important in determining if the laser/detector combination is sufficient to meet system requirements.
Laser (device) lifetime	Reliable, proven life of laser oscillator; worst case for continuous or intermittent use is taken.
Laser (pump)	Reliable, proven life of pump lamp for lasers using such pump.
Laser efficiency	Ratio of optical power (W) out of laser electrical power (W) into laser device. (Includes pump efficiency where pumps are used.)
Modulator figure of merit	Reciprocal of amount of electrical power into modulator (at maximum bandwidth).
Maximum bandwidth	For particular system concept, maximum bandwidth at which system will operate continuously.

TABLE 4. COMPARISON OF LASER COMMUNICATION SYSTEMS

Laser	λ, microns	Laser Power, W	Lifetime, hr		Laser Efficiency, %	Modulator Power, W	Modulator Figure of Merit	Maximum Bandwidth, Hz	$P_T/P_{R_{min}}$	Figure of Merit, M	Reason for Exclusion
			Device	Pump							
Argon	0.51	1.0	5,000		0.01	1.0	1.0	10^9	5×10^{17}	67	Low laser efficiency
Doubled YAG	0.53	0.3		500	0.03	1.1	0.9	10^9	1.6×10^{17}	53	Short pump life
He-Ne	0.6328	0.005	> 20,000		0.1	1.4	0.7	10^9	1.6×10^{15}	1	Low $P_T/P_{R_{min}}$
Ga-As	0.9	0.010	1,000		10	1.0	1.0	10^3	2.0×10^{15}	$\ll 1$	Low bandwidth
Nd:YAG	1.06 W pump	0.6		500	0.06	5	0.2	10^9	1.6×10^{16}	5.7	Low $P_T/P_{R_{min}}$ Short pump life
Nd:YAG	1.06 KR_B pump	0.1		10-400	0.03	5	0.2	10^9	2.7×10^{16}	0.499	Low $P_T/P_{R_{min}}$ Short pump life
Nd:YAG	1.06 LED pump	0.05		10-400	0.1	5	0.2	10^9	1.4×10^{16}	0.882	Low $P_T/P_{R_{min}}$ Short pump life
He-Ne	1.15	0.005	>20,000		0.1	5	0.2	10^9	1.1×10^{15}	<1	Low $P_T/P_{R_{min}}$
He-Ne	3.39	0.005	>20,000		0.05	2*	0.5	10^9	4.3×10^{16}	<1	Low $P_T/P_{R_{min}}$
CO_2	10.6	1.0	>10,000		10	12*	0.08	0.5×10^9	2.70×10^{19}	341	

*Intracavity coupling modulation.

He-Ne 0.6328 micron laser. The table shows a high value for M with argon, Nd:YAG operating at 0.53 microns, and for CO_2 lasers. The CO_2 system is the strongest contender on this basis and is used for the projected operational system in the schedule which follows.

Values for the power and lifetime of laser oscillators are chosen such that the power-lifetime product is maximized.

The schedule for a projected laser data relay satellite system is given in Figure 5. Here a TDRS system operating at RF is shown as beginning in 1975 with operation into 1982.

Currently (1973) laser experimental work is funded and will continue for component development. The development of a laser communication system that incorporates components is scheduled for CO_2 lasers during 1974, 1975, and into 1976. This would allow prototype development in 1976 and 1977 with launch in late 1977. The flight test of this experimental unit would be accomplished during 1978. Operational development flight and operation could be started during the same year, 1978, allowing launch in 1979 to 1980 and actual operation during the early 1980s. Thus, laser communication components that are presently being developed are suitable for an operational laser communication system for space data relays in the early 1980s.

Spacecraft Data Rate Requirements

The expected data rate for low earth orbiting users may be extrapolated from the present 30 Mbps data rate required by the multispectral scanner as shown in Figure 6. A manned space base and future scanners similar to the multispectral scanner require data rates in the order of 100 to 400 Mbps. These large data rates are required in the 1978 to 1980 time frame. This tends to determine the size of the type of data channel requirements needed for future data links; that is, data rates in the order of 100 to 500 Mbps. Since present RF links have data rates considerably smaller than this, it is appropriate to consider methods of data relay such as the laser data relay link.

The equivalent data rate capability through a synchronous satellite as provided by present communication satellites is given in Figure 7. Here, the equivalent data rate which may be passed through Intelsat I, III, and IV is indicated. In the case of Intelsat IV, the capacity indicated corresponds to the total capacity for four satellites. As may be seen, the total data rate handling capability is in the order of 1 Gbps. Thus, with two or three data collection sources, such as a manned space station or a high data rate multispectral scanner, the entire capacity of the present commercial data communication links would be required. Therefore, it is prudent to investigate other data link transmission means that do not depend upon such RF data relays.

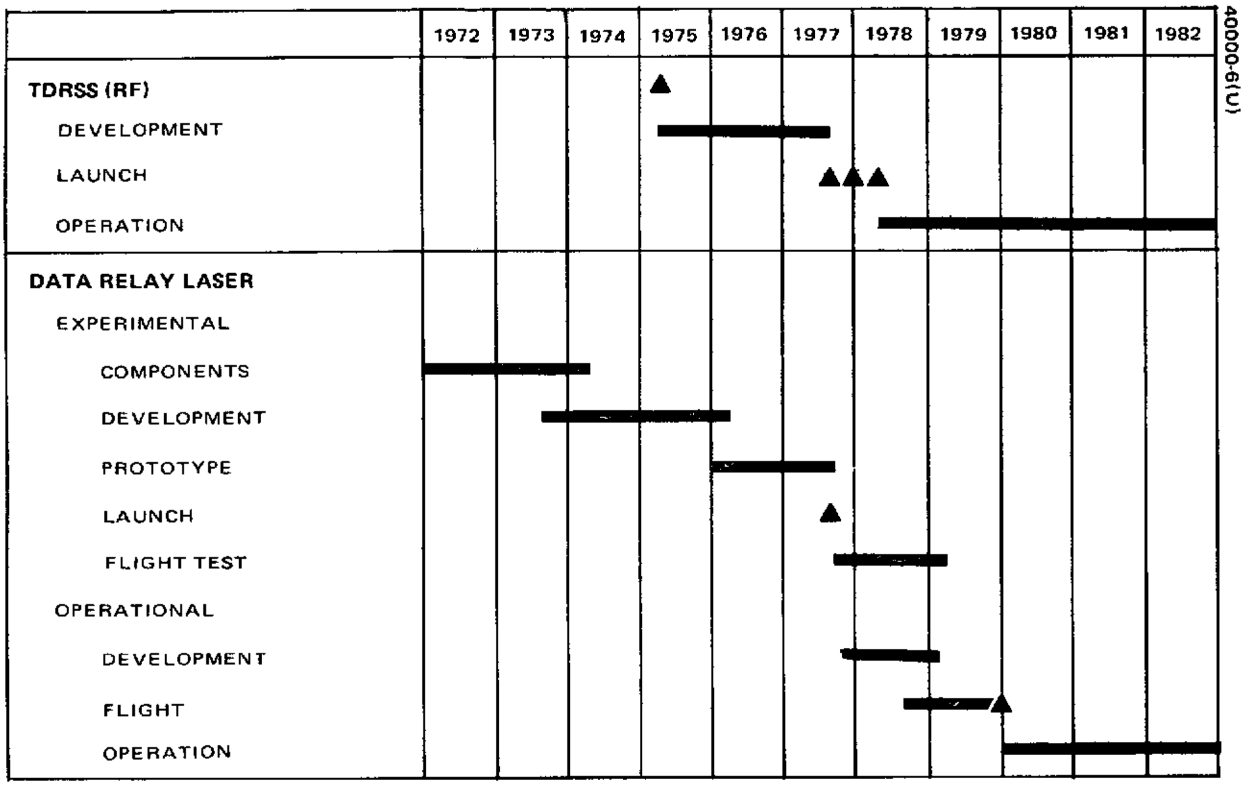


FIGURE 5. PROJECTED LASER DATA RELAY SATELLITE SYSTEM

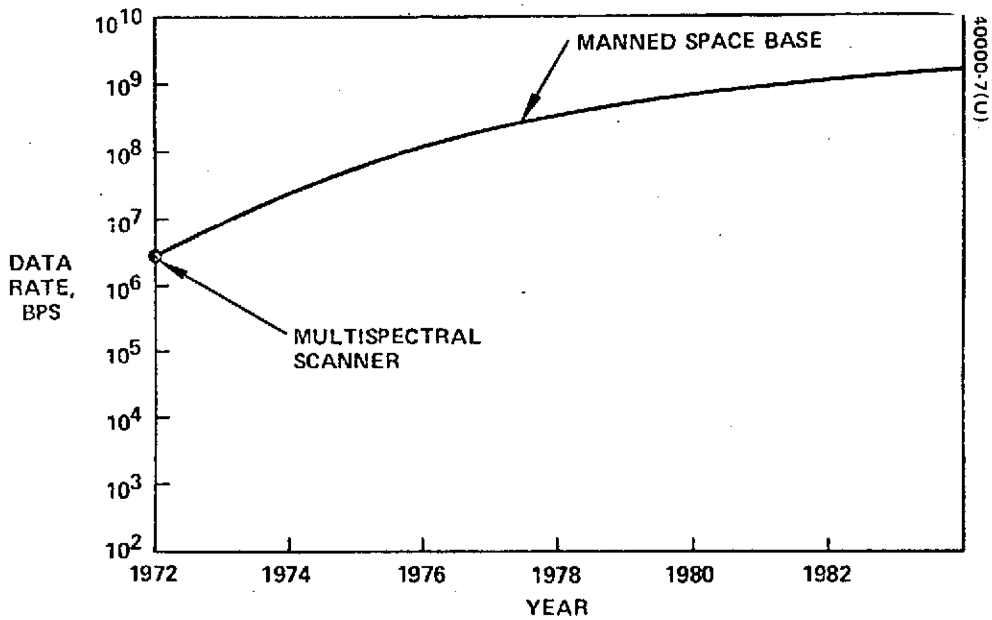


FIGURE 6. EXPECTED DATA RATES FOR LOW EARTH ORBIT USERS

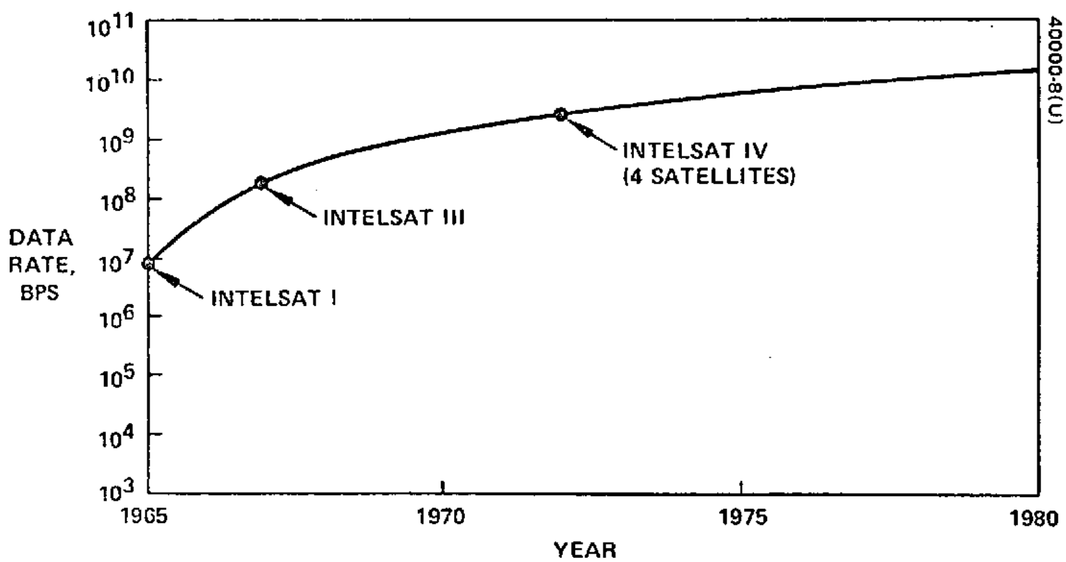


FIGURE 7. EQUIVALENT DATA RATES CAPABILITY THROUGH SYNCHRONOUS SATELLITE

Telemetry, Command, and Data Handling

This task has its main contribution in two areas. The first is a review of spacecraft systems to show trends in telemetry, command, and data handling; the second is a summary handbook for command and data handling.

The development of the onboard telemetry and data handling subsystem is constrained not only by the capabilities of the available ground support facilities but, more important, by the maximum allowed bit rate. The required bit rate is determined by the number of data sources and the sampling requirements of the sources as well as by the level of telemetry required from the spacecraft subsystems to fulfill the mission requirements. Comparison of the maximum permissible downlink bit rate with the mission bit rate requirement influences the degree of sophistication and complexity required in the telemetry and data handling subsystem. For instance, if the required bit rate conflicts with the permissible bit rate, it may be necessary to supercommutate certain data sources and subcommutate others.

Trends of in-command systems are indicated in Table 5, which compares an early and recent command system. Table 6 is similar but shows telemetry and data handling capabilities.

TABLE 5. COMMAND TREND COMPARISON

Spacecraft	Time Frame	Commands	Major Units*	Weight, lb	Power, W	Size, cu in
ATS-B	1966	256 pulse	2	13.7	4.0	438
OSO-I	1972	36 serial 576 pulse**	11	27.1	36.0	833

*Units such as command demodulator, command decoders, and command storage elements.
**Pulse commands are capable of turning a circuit on or off. Serial commands are capable of setting a value, e.g., time for a jet firing.

TABLE 6. TELEMETRY AND DATA HANDLING TREND COMPARISON

Spacecraft	Time Frame	Downlink Power and Bandwidth	Bit Rate	Format and No. of Inputs	Telemetry and Data Handling Subsystem				
					Apogee/ Perigee	Weight, lb	Power, W	Size, cu in	No. of Major Units*
ATS-B	1966	VHF: 2.1 W 30 kHz	194 bps	64 x 64 words 135 bi-level 140 analog Dwell/subcomm	36,000 km/ 36,000 km	16.6	5.2	547	4
OSO-I	1972	VHF: 1 W 30 kHz S band: 1 W 350 kHz	VHF: 6.4 kbps S band: 6.4 kbps or 128 kbps	128 x 128 words 544 inputs Dwell/subcomm Two sampling formats	550 km/ 550 km	73.9	61.2	2930	29

*Major units such as telemetry encoder and storage devices.

From a number of spacecraft the impact of the data handling subsystems on the spacecraft may be plotted. This is shown in Figures 8a through 8c for power, weight, and volume requirements as a function of the number of data channels.

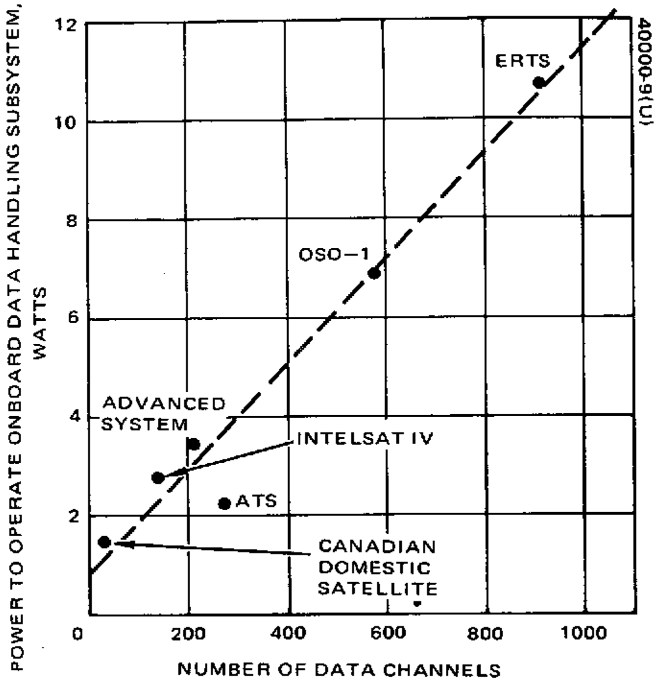
STDN Antenna and Preamplifier Cost Tradeoff Study

The cost effective combinations of preamplifier and antenna size to provide receiving system G/T performance have been calculated for many combinations of receiving antennas and RF preamplifiers under a variety of conditions including rain, antenna elevation angle, frequency, and post amplifier noise temperature. Typical results of such performance calculations are given in Figure 9 and Table 7.

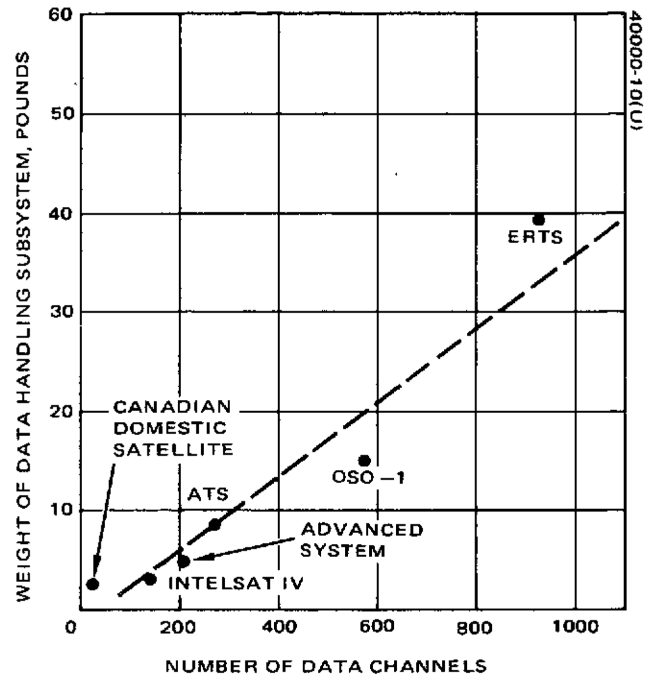
An advanced feed system has also been evaluated to determine under what conditions and for what type of station such a feed system would be cost effective compared to other means of improving performance. In this feed system for a ground antenna system, the feed horn configuration is constructed and phased to match the antenna field pattern at the image plane. (This is analogous to a filter matched to a particular waveform.) The significance of this feed system to this study is that such a feed is capable of improving the antenna efficiency and, thus, G/T for a certain cost. The question is then, "When is it advantageous to use such a feed?" Or, more generally, "When is it cost effective to update a given ground station configuration with a proposed improvement?" Such questions can be answered quantitatively two ways by using the data developed under this task.

The first way of answering the proposed questions is to run a computer analysis for both the unimproved and improved versions of the antenna feed. This form of the answer is conclusive but not always available to a user. However, the answer may also be quickly determined by using the data published in the task report, and the performance improvement and cost increase of the proposed change. Note that if a slope is formed which is the ratio of the cost of the proposed improvement to the change in system G/T, this slope may be compared to a reference set of points such as is found in the complete task report. Whenever this slope is greater than the slope between two adjoining points of the reference set, the proposed improvement is not cost effective; however, if the slope is less than the slope between two adjacent points on the reference curve, it is cost effective. This slope comparison is illustrated in Figure 10 for each point. In the example, the slope of dollar cost to dB improvement in system G/T, \$150,000/1.0 dB, is only less than the reference curve without the matched feed at the points indicated by deltas. At these points it would be cost effective to use the new feed to improve system G/T rather than another method.

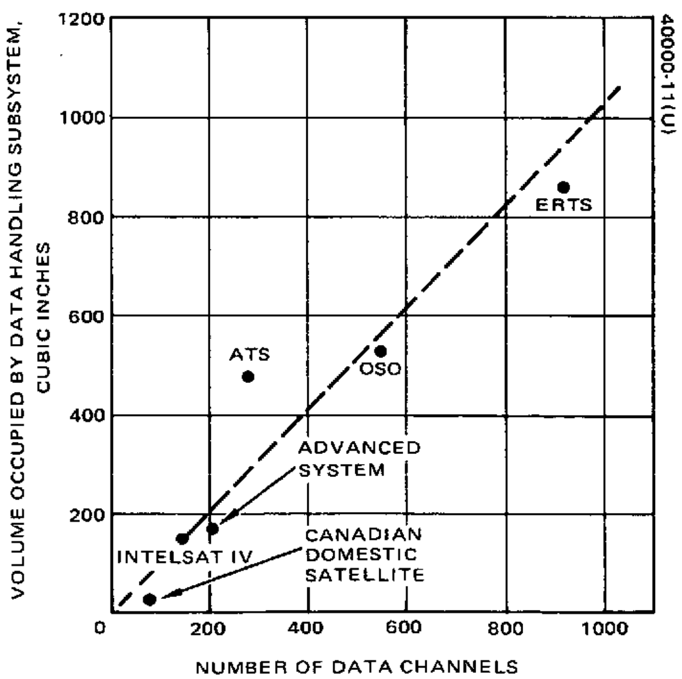
During the investigation of STDN parameters a wide variation was found in the input RF loss among the various stations, due to a number of causes, including switching for various preamplifiers and long transmission lines. The G/T performance is very sensitive to this early loss in the receiver system. Figure 11 illustrates this effect by showing the change in a typical system noise temperature caused by RF loss using a variety of preamplifiers.



a) POWER REQUIREMENT AS FUNCTION OF NUMBER OF DATA CHANNELS



b) WEIGHT AS FUNCTION OF NUMBER OF DATA CHANNELS



c) VOLUME AS FUNCTION OF NUMBER OF DATA CHANNELS

FIGURE 8. DATA HANDLING SUBSYSTEM

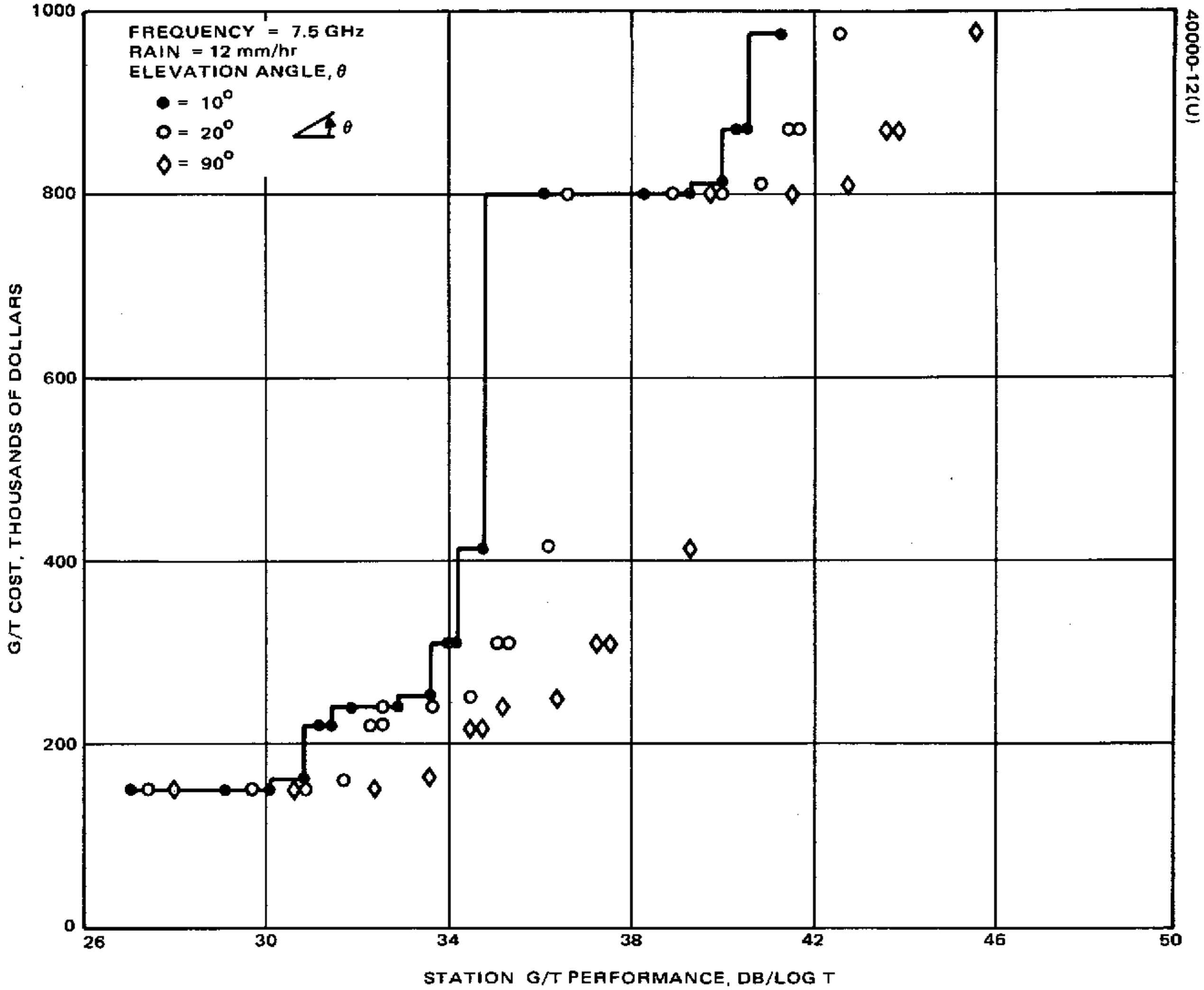


FIGURE 9. X BAND COST EFFECTIVE G/T PERFORMANCE WITH RAIN

TABLE 7. X BAND PERFORMANCE DATA (12 MM/HR RAIN)

Cost, dollars	G/T, dB/log T	Preamplifier Type	Preamplifier Temperature, ^{o}K	Antenna Diameter, m
10^{o} elevation angle				
151300	27.0	TDA, 80	410	9.14
151800	29.1	Transistor, 80	175	9.14
152500	30.1	Transistor, 80	90	9.14
160000	30.8	Paramp, 80	45	9.14
220000	31.2	Paramp, 73	21	9.14
220000	31.3	Paramp, 80	14	9.14
241800	31.9	Transistor, 80	175	12.19
242500	32.9	Transistor, 80	90	12.19
250000	33.6	Paramp, 80	45	12.19
310000	34.0	Paramp, 73	21	12.19
310000	34.1	Paramp, 80	14	12.19
415000	34.8	Maser, 80	5	12.19
801300	36.2	TDA, 80	410	25.91
801800	38.3	Transistor, 80	175	25.91
802500	39.3	Transistor, 80	90	25.91
810000	40.0	Paramp, 80	45	25.91
870000	40.4	Paramp, 73	21	25.91
870000	40.5	Paramp, 80	14	25.91
975000	41.3	Maser, 80	5	25.91
20^{o} elevation angle				
151300	27.4	TDA, 80	410	9.14
151800	29.7	Transistor, 80	175	9.14
152500	30.9	Transistor, 80	90	9.14
160000	31.8	Paramp, 80	45	9.14
220000	32.3	Paramp, 73	21	9.14
220000	32.5	Paramp, 80	14	9.14
241800	32.5	Transistor, 80	175	12.19
242500	33.8	Transistor, 80	90	12.19
250000	34.6	Paramp, 80	45	12.19
310000	35.1	Paramp, 73	21	12.19
310000	35.3	Paramp, 80	14	12.19
415000	36.2	Maser, 80	5	12.19
801300	36.6	TDA, 80	410	25.91
801800	38.9	Transistor, 80	175	25.91
802500	40.2	Transistor, 80	90	25.91
810000	41.0	Paramp, 80	45	25.91
870000	41.5	Paramp, 73	21	25.91
870000	41.7	Paramp, 80	14	25.91
975000	42.6	Maser, 80	5	25.91
90^{o} elevation angle				
151300	28.0	TDA, 80	410	9.14
151800	30.7	Transistor, 80	175	9.14
152500	32.4	Transistor, 80	90	9.14
160000	33.6	Paramp, 80	45	9.14
220000	34.5	Paramp, 73	21	9.14
220000	34.7	Paramp, 80	14	9.14
242500	35.2	Transistor, 80	90	12.19
250000	36.4	Paramp, 80	45	12.19
310000	37.3	Paramp, 73	21	12.19
310000	37.5	Paramp, 80	14	12.19
415000	39.3	Maser, 80	5	12.19
801800	40.0	Transistor, 80	175	25.91
802500	41.6	Transistor, 80	90	25.91
810000	42.8	Paramp, 80	45	25.91
870000	43.7	Paramp, 73	21	25.91
870000	43.9	Paramp, 80	14	25.91
975000	45.7	Maser, 80	5	25.91

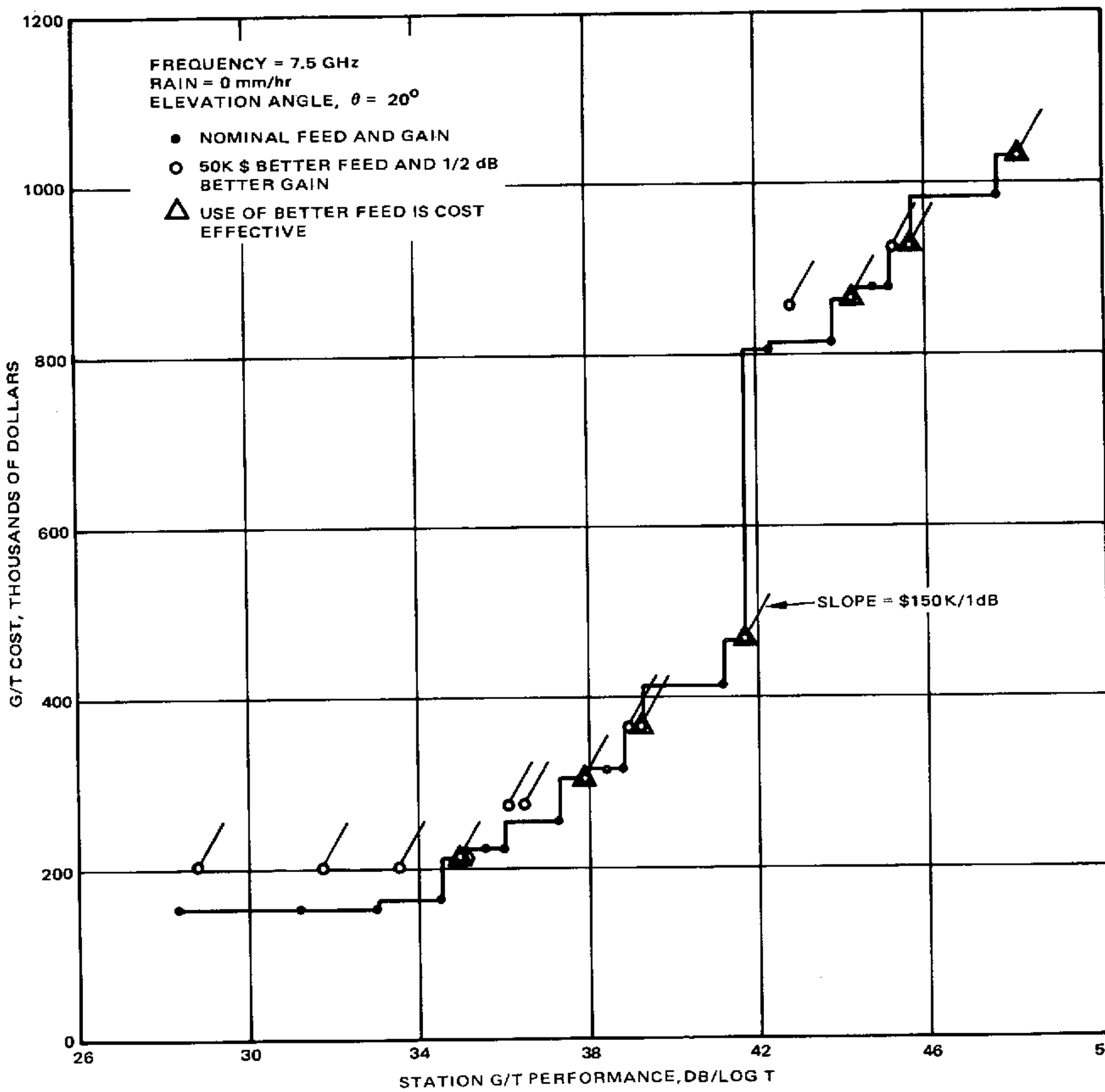


FIGURE 10. X BAND COST EFFECTIVE G/T FEED HORN COMPARISON

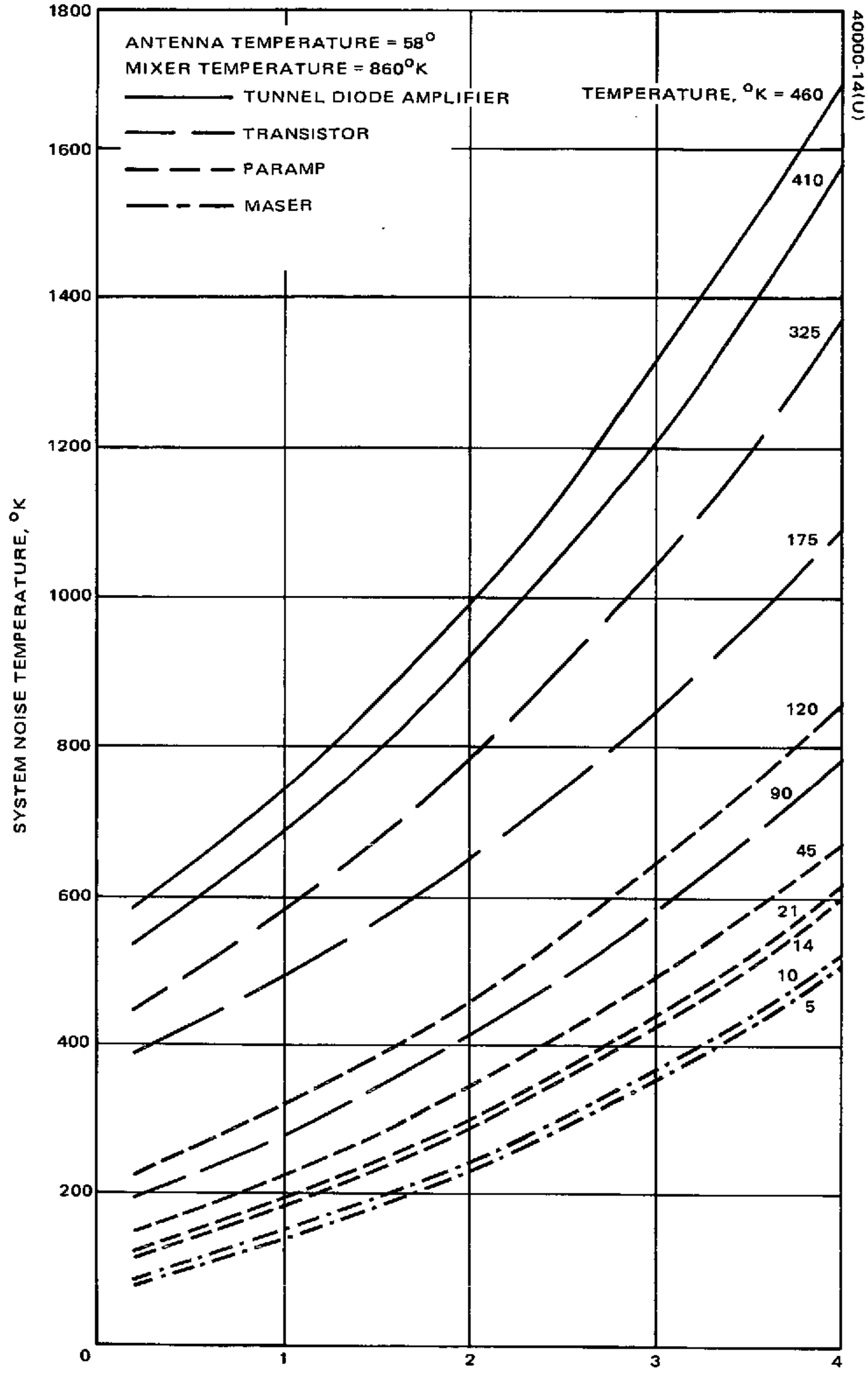


FIGURE 11. EFFECT OF RF CIRCUIT LOSS ON SYSTEM NOISE TEMPERATURE IN X BAND RECEIVING SYSTEM

The significance of this loss is shown by its overall effect on system noise temperature for a change of loss of 1 to 2 dB. This change can cause an overall change in system G/T by 1.3 to 3.2 dB depending upon the particular preamplifier used; the larger changes in G/T occur with the more sensitive preamplifiers.

Spacecraft Communication Terminal Evaluation

An analytical comparison is made of space communication accomplished at 6 different wavelengths. In the radio band, 2.25, 7.5, and 14.5 GHz systems are analyzed, whereas at optical wavelengths 0.53, 1.06, and 10.6 micron systems are examined. The purpose of the comparison is to determine which of these systems will require the least hardware weight to perform a given communication task. This is determined by requiring each communication system to meet a given bit error rate while selecting combinations of transmitted power and antenna diameter to obtain the least overall system weight. This performance is provided while maintaining practical values for parameters other than antenna diameter and power, which also affect system performance.

The results of the analysis indicate that for future data links over ranges of 42,000 to 84,000 km and with data bandwidths of 100 to 1000 MHz, the CO_2 laser communication system will provide the required performance with the least total system weight impact on a spacecraft.

The analytical method, which determines the spacecraft link parameters to provide a given performance at a minimum weight, has two basic parts: 1) the equation that relates all the communication parameters to a measure of signal transmission quality, usually the bit error rate; and 2) a series of equations that relate component weights to component parameter values. The analytical method determines the lightest weight combination of components to achieve the desired performance, which is defined as the best system.

To perform the weight optimization, it is required to select values for the performance equation (bit error rate), using the weight equations as a criterion. All the weight relationships ultimately depend on either the antenna diameter or the transmitted power. The minimum weight solution may then be found by the following steps:

1) Selecting a trial value of diameter for the transmitting aperture

2) Determining the value of transmitted power to satisfy the bit error rate

3) Determining the total communication system weight resulting from these values of power and diameter using the weight relationships

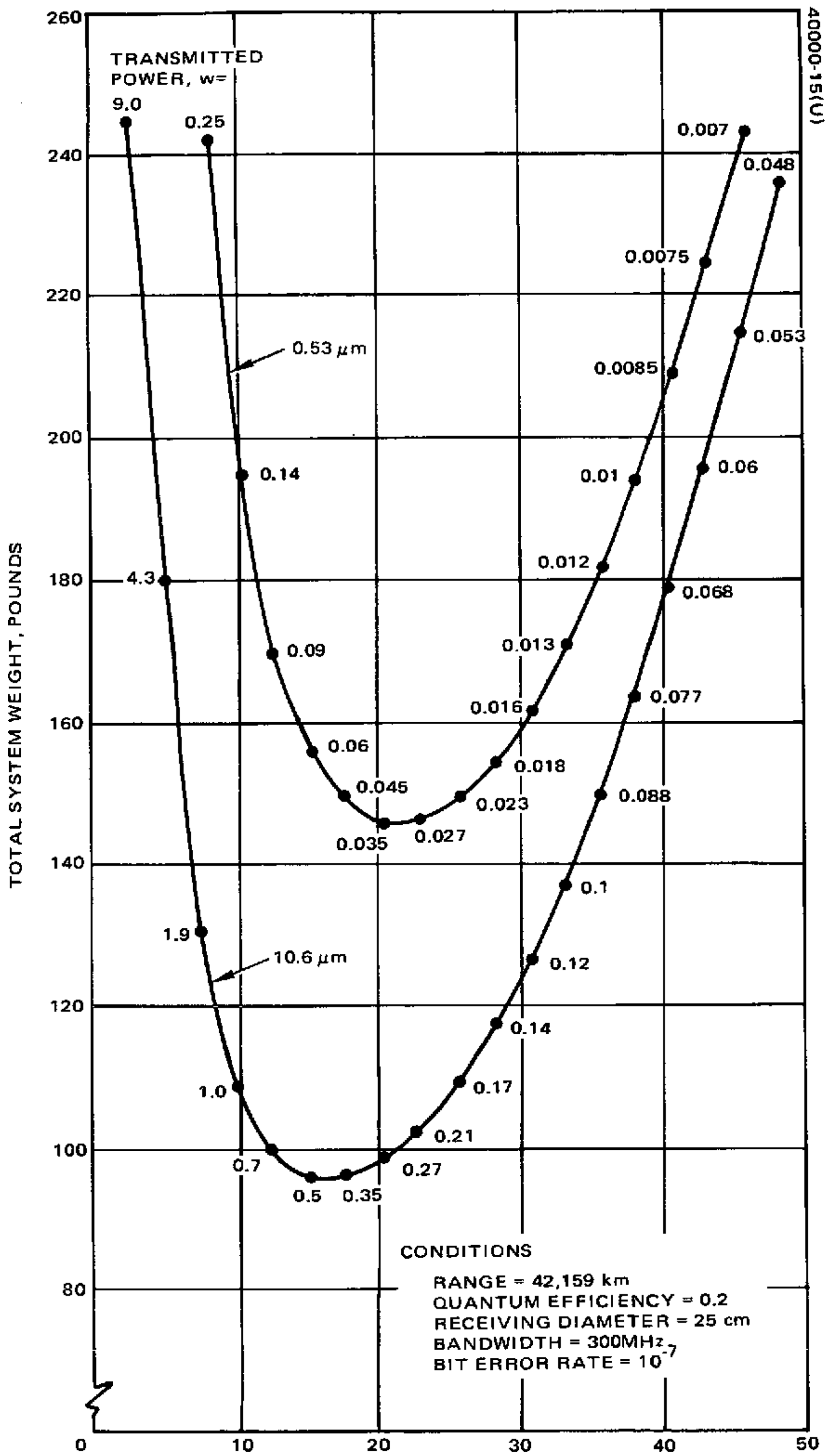


FIGURE 12. SYSTEM WEIGHT DEPENDENCE UPON TRANSMITTER APERTURE DIAMETER AND TRANSMITTED POWER

4) Repeating steps 1, 2, and 3 using a new value of diameter; if the new value of total communication system weight is less than that found in step 3, repeat steps 1, 2, and 3 until the total weight of the repeated set is greater than the prior set

5) Selecting the smallest weight system*

The selection of transmitted power and transmitting aperture size to produce a minimum weight system is illustrated graphically in Figure 12, where the total weight of two optical systems is shown as a function of transmitting aperture diameter. The numbers on the curves indicate the corresponding transmitted power required at each point. At every point on the curve, the value of transmitted power and transmitting diameter would provide the required performance. The curves show, however, that there is a best combination that requires the least total weight.

The optimization procedure was implemented as a computer program and a large number of cases were run, illustrating how total system weight** is affected by bandwidth, detector quantum efficiency, detector gain, transmitter efficiency, wavelength, and detection method. Figures 13 to 17a and 17b illustrate these variations.

The weight of radio systems was also calculated. Figure 18 is a composite comparison of radio and optical systems using 1973 and 1980 state of the art. This figure indicates that the CO_2 system is the lightest weight system for data rates of 10^8 to 10^9 bits per second for ranges of 42, 000 km to 84, 000 km.

*Note that this process is iterated in decade increments to obtain exact minima.

**Nonredundant transmitter and receiver plus the spacecraft power supply and heat radiation hardware to support the transceiver.

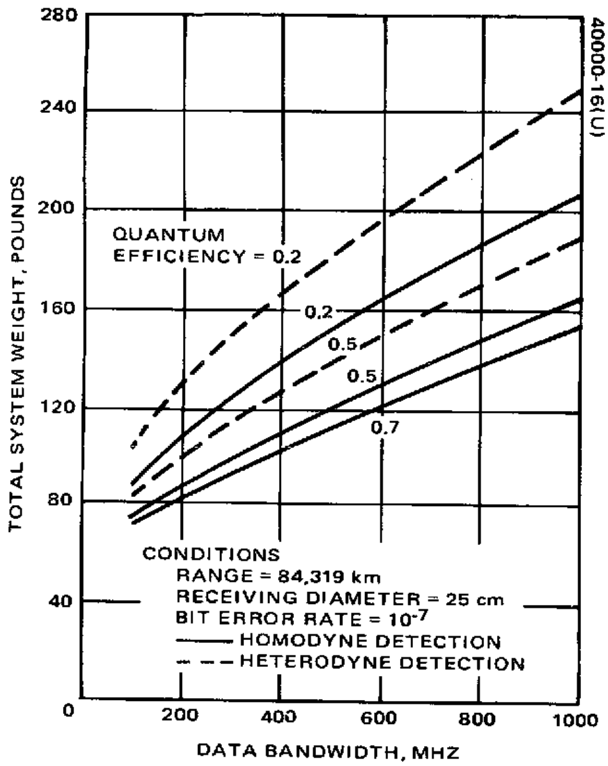


FIGURE 13. EFFECT OF DETECTOR QUANTUM EFFICIENCY ON 10.6 MICRON COMMUNICATION SYSTEM WEIGHT FOR WEIGHT OPTIMIZED SYSTEMS

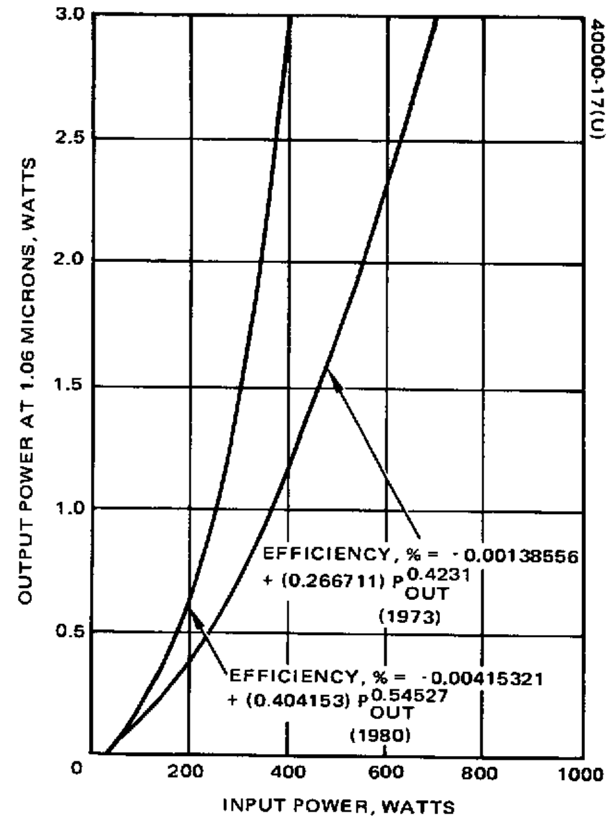


FIGURE 14. TRANSMITTER INPUT POWER REQUIREMENTS FOR 1.06 MICRON POWER

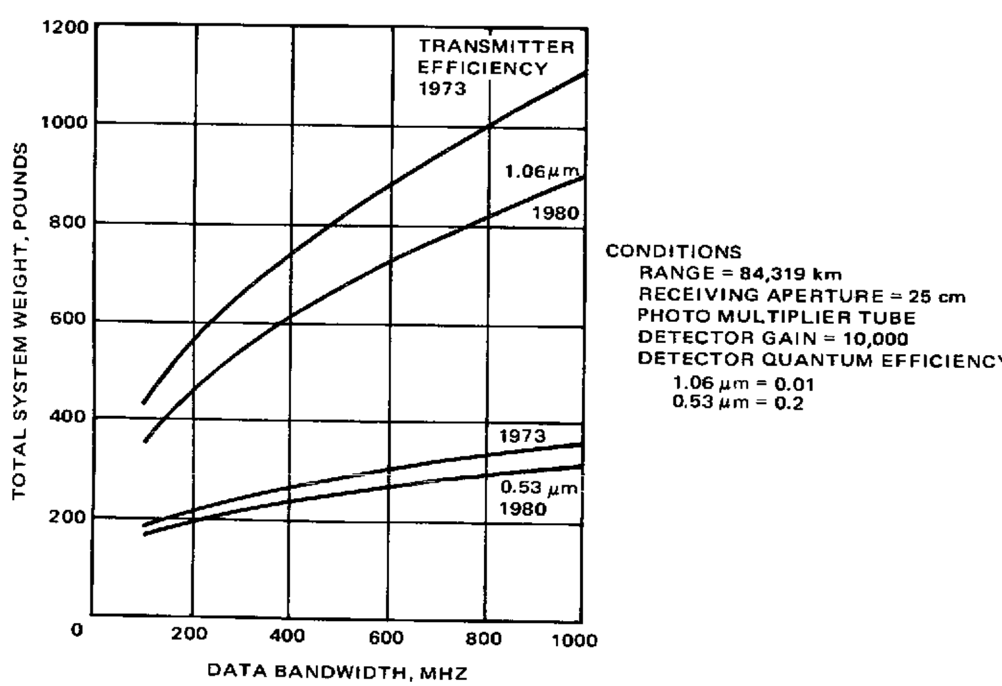


FIGURE 15. EFFECT OF TRANSMITTER EFFICIENCY ON OVERALL COMMUNICATION SYSTEM WEIGHT FOR 1.06 AND 0.53 MICRONS

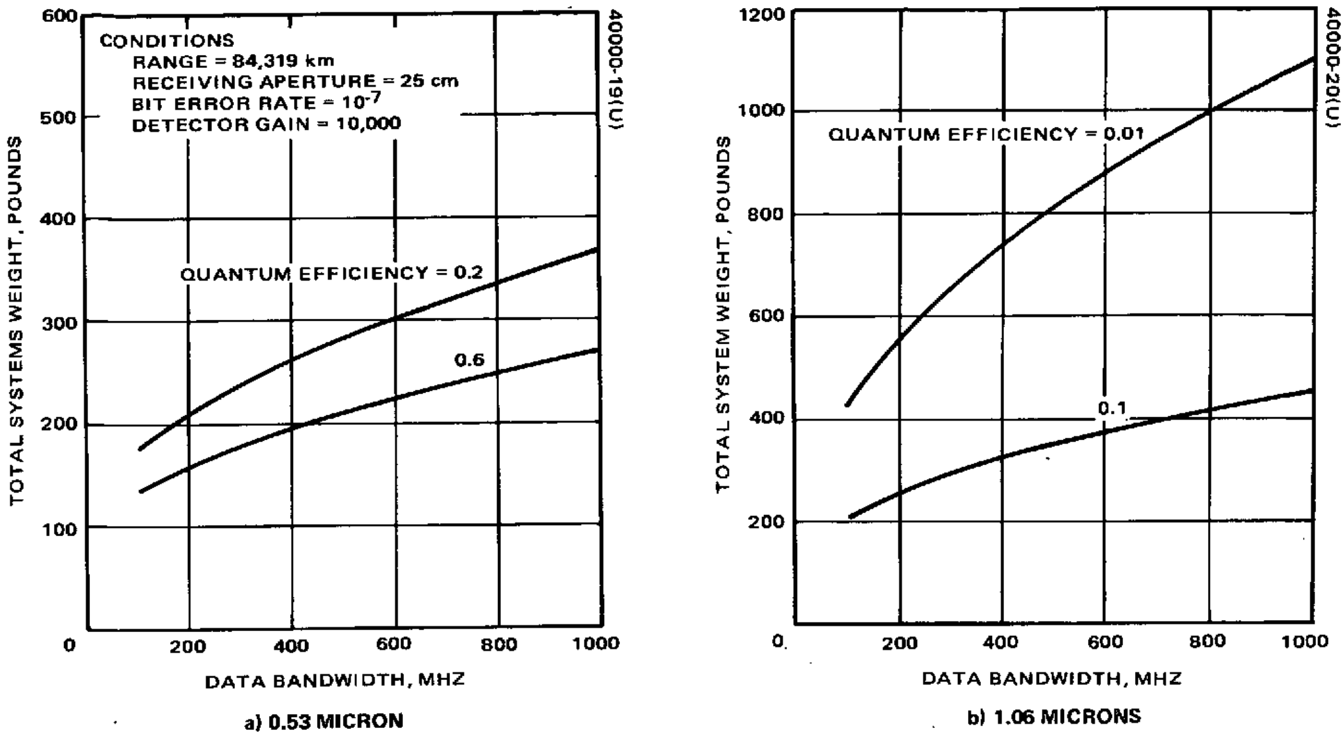


FIGURE 16. EFFECT OF DETECTOR QUANTUM EFFICIENCY ON COMMUNICATION SYSTEM WEIGHT FOR WEIGHT OPTIMIZED SYSTEM

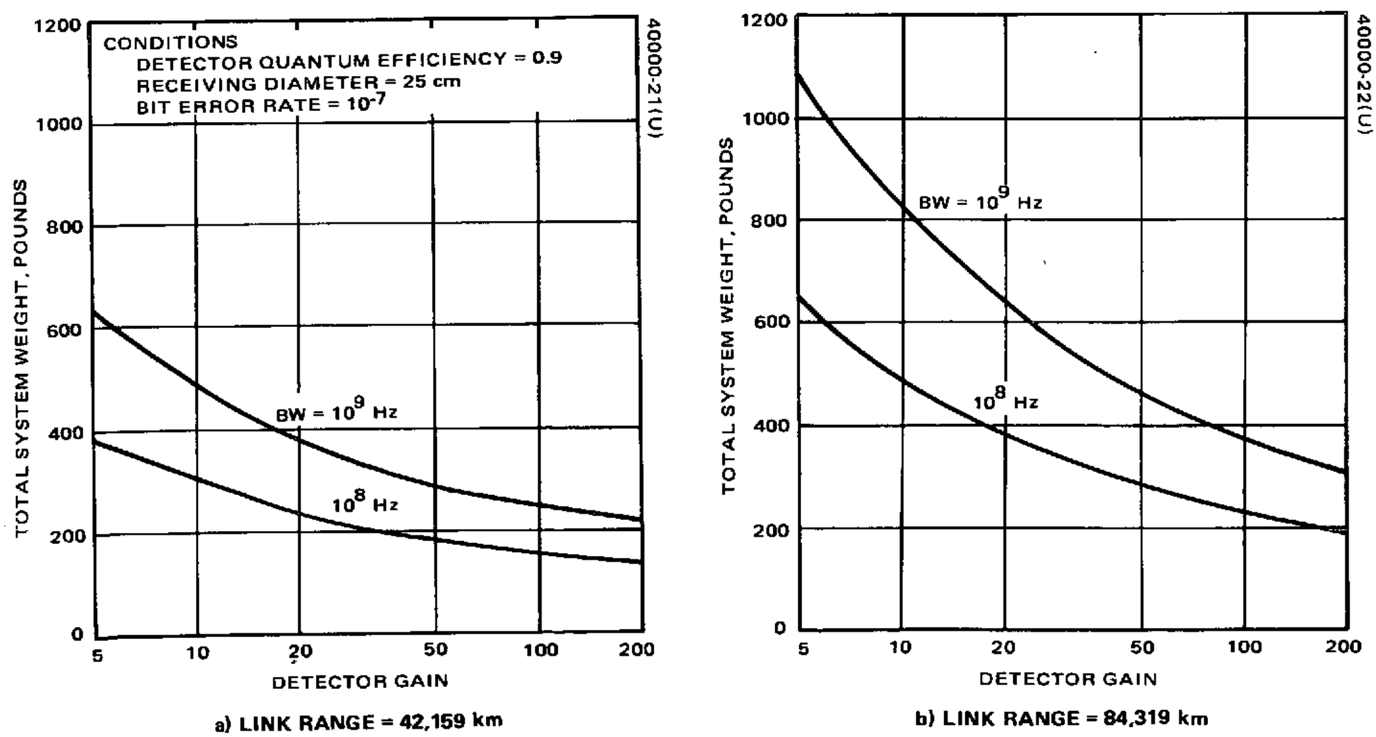


FIGURE 17. EFFECT OF PHOTODIODE GAIN ON SYSTEM WEIGHT

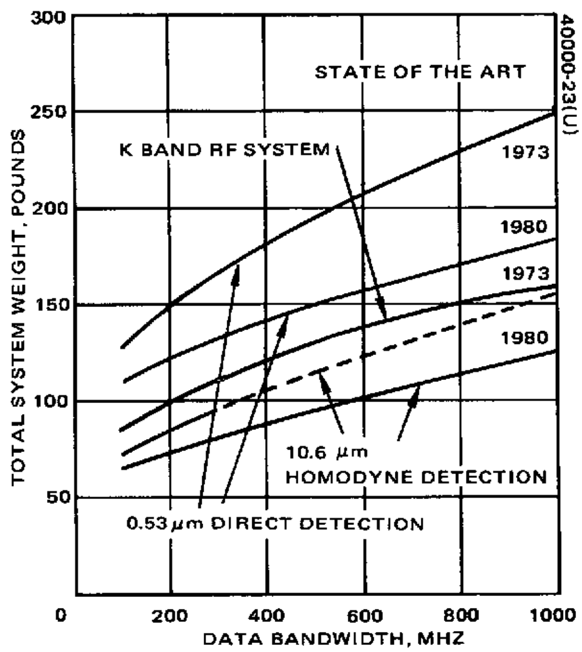


FIGURE 18. COMPARATIVE TOTAL SYSTEM WEIGHTS FOR THREE COMMUNICATION SYSTEMS IN DATA RELAY CONFIGURATION, RANGE OF 42,159 km

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have come from this study contract:

1) Data rates for space communication are projected to increase from 10^8 to 10^9 bits per second during the 1973 to 1980 time frame.

2) Laser technology is developed to a point to where laser communication systems for spaceflight test can be operated in 1977 and operational systems can be in service by 1980.

3) Onboard data compression is promising as a means of reducing data rates for space and subsequent earth links.

Four significant factors have occurred that direct increased interest toward spaceborne data compression. They are the development of large-scale integrated circuits providing extremely small components suitable for onboard processing; the development of new data compression techniques; the use of the onboard computer for processing other than data compression; and the economic advantages resulting from early reduction of the data bandwidth.

4) Development of onboard computer control of a spacecraft's telemetry subsystem should be emphasized. This can be used to assist in data compression as well as to maintain a limit on the downlink data rate on a complex spacecraft by flexible data formatting.

The telemetry format should be continually reconfigured to meet current demands for data transmission. Thus, a very complex spacecraft containing more data sources than could be simultaneously accommodated by the telemetry subsystem could be reconfigured rapidly to accommodate the most appropriate data for transmission.

An important side effect of onboard computer control is that a more generally useful spacecraft bus may result due to the programmable nature of the telemetry subsystem. Command functions and attitude control problems could be solved by the same computer. Thus, the overall effect of an onboard computer could be a considerable cost savings.

5) The development of low noise transistor amplifiers at S, C, X, and K bands should be continued. These units are projected to replace tunnel diode amplifiers in the 1980 time frame.

6) Parametric amplifiers, both cooled and uncooled, should have development effort continued, because they provide performance that is almost equal to the maser and is certainly cost competitive.

7) STDN station antennas should be individually examined to determine what means can be used to reduce their RF cable and waveguide losses and which stations could profitably utilize a better feed configuration.

8) Since the CO_2 laser system has the potential of lightweight hardware to perform wideband data transmission, it is recommended that emphasis be increased on this promising communication system. It is further recommended that emphasis be increased on detector performance improvements (e.g., quantum efficiency) and detection method improvements (e.g., homodyne detection).

9) There is a high productivity in reducing total communication system weight by improving the optical detectors. This is apparent in Figure 17 where improvements in detector gain of a photodiode cause high reduction in overall system weight. The effect on weight through optical detection improvement is also seen in Figure 13 and 16. Here the effect of quantum efficiency and type of detection on overall system weight can be seen.